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Mechanical properties and performance under laboratory and field conditions of a lightweight fluorogypsum-based blend for economic artificial reef construction

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Abstract

This paper investigates the mechanical properties under laboratory and field conditions of a concrete-like blend made of fluorogypsum (FG), fly ash, and Portland cement for artificial reef construction, which is referred to as FG-based blend. The 28-day compressive strength and relative volumetric expansion of the FG-based blend were statistically characterized. After one year of immersion in brackish water under field conditions, the compressive strength of the FG-based blend experienced a moderate reduction when compared to material under laboratory conditions, but did not degrade below its 28-day value. Visual examination of the immersed specimens indicated that aquatic organisms are attracted to the proposed material. Field investigation of a small artificial reef structure made of a FG-based blend indicated that sea floor settlement due to the weight of the structure was small. A preliminary cost analysis comparing the cost of artificial reefs constructed with different materials suggests that the proposed FG-based blend is a promising environment-friendly economic material for artificial reef construction.

Key words: industrial by-products, beneficial reuse, green concrete, fluorogypsum, fly ash, Portland cement, artificial reef.

Introduction

The coastal areas of the United States are densely inhabited regions that are also strategically important for the US economy, e.g., through their contribution to tourism, fisheries, recreation, and oil and gas. Several diverse natural and anthropogenic disturbances can affect the quality of life and economic productivity of the US coastal regions, e.g., pollution, extreme weather events, and erosion (Lal and Stewart 2013). Coastal erosion is a particularly severe issue in the US Gulf Coast due to an unfavorable combination of rising sea levels and increasing cyclone intensity, which produce increasing storm surges and wave loads that contribute to accelerate the erosion process (LCWCR/WCRA 1999). The annual land loss from coastal erosion in the State of Louisiana alone ranges between 57-90 km^2 (LCWCR/WCRA 1999). In the State of Florida, out of 2,170 km of coastline, 30% are critically and 7% are non-critically eroded; whereas, out of 13,560 km of inlet shoreline, 14 km are critically and 5 km are non-critically eroded (Irwin 2016; US Census Bureau 2012). Coastal erosion and land loss contribute to exacerbate the damage to the natural and built environment produced by extreme weather events and, thus, negatively impact the environment and the economy (Phillips and Jones 2006; FitzGerald et al. 2008). Therefore, protecting these coastal areas from erosion is of paramount importance.

Three main approaches are commonly used to mitigate the effects of coastline erosion: (1) hard-erosion control systems, such as seawalls and groins; (2) soft-erosion control systems, such as sandbags and beach nourishments; and (3) relocation, i.e., moving residential constructions, communities, commercial activities, and industrial facilities away from the coast (Knapp 2012). Hard-erosion control structures are the most commonly used coastline protection systems for critical erosion. Among these systems, artificial reefs provide a solution that, in addition to protecting the coastline from erosion, can be used to enhance marine life and sustain the local fishery industry for high-value aquatic species, e.g., oysters and crabs. However, the high costs associated with the materials and construction of these protection devices pose severe limitations on their usage. Crushed recycled concrete, limestone, granite, and other stones used for construction of coastal erosion control systems built using loose materials (e.g., artificial reefs, revetments, groins, and detached breakwaters) are expensive materials and are usually not readily available in the US Gulf Coast. For instance, limestone represents the most commonly used material for dike construction in the State of Louisiana; however, the cost of this material can be significant because it is mined in Arkansas and transported to Louisiana before it can be used, with an average cost at delivery of $36-$52/ton in 2001 (Rusch et al. 2005). Similarly, in the state of Florida, granite is commonly used as riprap to protect shorelines; however, the production and transportation costs of this material amounted to an average of $35/ton in 2003 (Rusch et al. 2005) and of $31-60/ton in 2007 (Rusch et al. 2010). In addition to these cost issues, the usage of heavy materials is incompatible with the soft seabed of the US Gulf Coast. Close to two-thirds of limestone reefs are known to sink into the underlying soft sediment within few months after placement along the coast of Louisiana (Schexnayder M., Louisiana Department of Wildlife and Fisheries, Personal Communication 2014). Since thousands of tons of construction materials are needed for a single coastal protection project (Lukens and Selberg 2004; CPRA 2013), the identification of more cost-effective, lower unit mass materials would increase the likelihood of project implementation, reduce needed material volume, and extend the service life of artificial reefs in the US Gulf Coast.

Concrete-like blends based on by-product gypsum (a low-cost, locally available material) have been the subject of significant research efforts (Yan and You 1998; Peiyu et al. 1999; Yan and Yang 2000; Rusch et al. 2001; Rusch et al. 2005; Sing and Garg 2009; Escalante-Garcia et al.

2009; Martinez-Aguilar et al 2010; Magallanes-Rivera and Escalante-Garcia 2014; Garg and Pundir 2014; Huang et al. 2016; Garg and Pundir 2017). Fluorogypsum (FG), an acidic by-product (pH = 2.3) generated by the industrial manufacturing of hydrofluoric acid (Chesner et al. 1998), is commonly stockpiled after addition of alkali materials and referred to as blended calcium sulfate (Tao and Zhang 2005) or pH-adjusted FG (Bigdeli et al. 2018a). Earlier research on FG-based blends focused on their stabilization for use as sub-base course material for road construction (Tao and Zhang 2005). More recent research on the use of FG-based blends suggested that these materials could present several advantages over the use of crushed concrete and limestone in artificial reef construction, e.g., lower cost, lower carbon footprint, and vast availability in the Southeastern coastal regions (Bigdeli and Barbato 2017; Lofton et al. 2018; Bigdeli et al. 2018a; Bigdeli et al. 2018b). However, significant research is still needed to assure an appropriate performance of FG-based blends in large-scale artificial reef systems. Albeit fundamental to determining an optimal construction process, the literature on the relation between mechanical properties and curing time of this material is scarce, while data on long-term performance in submerged conditions is non-existent. In addition, the typical variability of these mechanical properties has not been characterized in the literature. Performance data related to changes in material mechanical properties and overall structural stability over time are required to inform the design of these coastal protection systems.

This paper aims to reduce the knowledge gap that is inhibiting the use of FG-based blends in aquatic applications, with a particular focus on non-load-bearing artificial reefs made of loose materials and located in the US Gulf Coast region. The main objectives of this research were to: (1) characterize the compressive strength and relative volumetric expansion properties of FG-based blends, as well as their variability, after a 28-day curing in laboratory conditions; (2) quantify the effects of curing time on the compressive strength and relative volumetric expansion of FG-based blends; (3) compare the compressive strength of FG-based blends in laboratory conditions with the corresponding compressive strength obtained in field conditions after prolonged immersion in brackish water; (4) assess the long-term performance and global stability of a small scale FG-based artificial reef; and (5) compare the cost of the proposed material to that of other materials commonly used for artificial reef construction through a simplified cost analysis. This study focused on compressive strength and relative volumetric expansion because they were identified as the most important properties to characterize the mechanical performance of FG-based blends (Yan and You 1998; Bigdeli et al. 2018b). Previous investigations also showed that these two material properties can be used as proxies of both short-term and long-term performance of aquatic structures built using FG-based blends (Bigdeli and Barbato 2017; Lofton et al. 2018; Bigdeli et al. 2018a; Bigdeli et al. 2018b). In particular, a compressive strength $f_c \geq 4.0$ MPa and a relative volumetric expansion $\eta \leq 6.0\%$ have been recommended for the type of applications considered in this study (Bigdeli et al. 2018b). An FG-based blend made of 62% pH-adjusted FG, 35% class C fly ash (FA), and 3% Portland type II cement (PC) was selected for this study based on previous research performed by the authors (Bigdeli et al. 2018b). This specific composition was identified as a promising material for artificial reef construction based on its 28-day compressive strength (Bigdeli et al. 2018b) and 77-day dynamic leaching properties, which indicate that the considered composition does not completely dissolve under prolonged submersion in freshwater, brackish water, or saltwater (Lofton 2017; Bigdeli and Barbato 2017; Lofton et al. 2018).

Experimental Investigation of FG-Based Blends: Materials and Methods

Characterization of raw materials

The raw materials used in this study were pH-adjusted FG, FA, and PC. The pH-adjusted FG was obtained from the stockpiles located in Geismar, LA. It is noted here that the stockpiled pH-adjusted FG contained grains of size of a 2-cm maximum diameter and was utilized as provided by the producer. The fly ash was produced at the Big Cajun II power plant in New Roads, LA. The PC was obtained from a local supplier in Darrow, LA. The crystallographic compositions of the materials were identified based on X-ray diffraction analyses. The results of the Rietveld analyses (Young 1993) for the pH-adjusted FG, FA, and PC used in this work are summarized in Table 1 and are described in detail elsewhere (Bigdeli et al. 2018a; Bigdeli et al. 2018b; Lofton et al. 2018).

Specimen preparation and experimental tests for compressive strength and volumetric expansion

The pH-adjusted FG was dried at a temperature of 45 °C for a period of 14 h before preparation of the experimental specimens, according to ASTM D2216 (ASTM 2010). The dry components of pH-adjusted FG, FA, and PC were machine mixed together into a homogeneous blend, and then mixed with water (Bigdeli et al. 2018b). The dry portion of this is blend contained 62% of pH-adjusted FG, 35% of FA, and 3% of PC by weight. The water amount was 20% of the total weight of dry material. The final material after hardening was a concrete-like blend as it contained binding material, water, air, fine aggregate, and coarse aggregate, which consisted of the larger grains of pH-adjusted FG.

Eighty cylindrical specimens of the FG-based blend with a size of 10.2 cm x 20.4 cm (4 in x 8 in) were prepared according to ASTM C192 (ASTM 2016a). Sixty specimens (group 1) were cured under laboratory conditions at 100% relative humidity (in a moisture room) and constant room temperature (21±2 ˚C). Of these 60 specimens in group 1, 20 were used to characterize the statistical variability of compressive strength and relative volumetric expansion after a 28-day curing cycle, which is generally considered the reference condition for concrete-like materials. Characterization of the statistical variability of mechanical and physical properties of FG-based blends (i.e., compressive strength and relative volumetric expansion, respectively) is crucial to determine the reliability of structures built using these materials, as well as to assess their performance in a probabilistic sense. The other 40 specimens of group 1 were used to identify the effects of curing time on the compressive strength and relative volumetric expansion over a one-year period (five specimens each at 7, 14, 56, 121, 133, 208, 298, and 393 days after specimen preparation).

The remaining 20 specimens (group 2) were cured in laboratory conditions (i.e., 100% humidity and 21±2 ˚C) for 28 days and then placed on the sediment floor in a brackish water bay (with an average salinity of 19.82±0.04 ppt and a range measured over a 15-month period of 5.5-35.0 ppt) adjacent to the Louisiana Department of Wildlife and Fisheries Research Lab in Grand Isle, LA. These cylinders were exposed to the actual field conditions at the site, i.e., subject to uncontrolled environmental actions (e.g., sea waves, current loads, and temperature fluxes) and interactions with aquatic organisms (e.g., surface attachment, penetration, and boring). The purpose of the field test was to investigate the effects of prolonged brackish water immersion on the compressive strength of the FG-based materials over a one-year period. Groups of five specimens were tested for compressive strength after 105, 180, 270, and 365 days of submersion. Due to inclement weather, the first set of samples were collected from the bay on day 105 (with 15 days delay) rather than at 90 days, as originally planned. Visual examination of the retrieved immersed specimens before compressive strength testing was used to determine if the FG-based blend provides an attractive substrate for useful aquatic organisms.

Compressive strength was measured according to ASTM C39 (ASTM 2016c). Relative volumetric expansion was estimated at the various curing ages considered in this study (i.e., 7, 14, 28, 56, 121, 133, 208, 298, and 393 days after specimen preparation) by measuring volume changes through the standard tools described in ASTM C1005 (ASTM 2017) because the methods recommended in the ASTM standards for cement paste and concrete were not appropriate for the FG-based blend used in this study, as discussed in Bigdeli et al. (2018a). In particular, the relative volumetric expansion was calculated as the ratio between the change in volume and the initial volume measured through the water displacement in a graduated cylinder 5 ml graduation lines, as described in Bigdeli et al. (2018b). Statistical significance of the differences in experimental results was assessed using the one-way analysis of variance (ANOVA) test (Box et al. 1978) with a 5% confidence level, unless otherwise noted.

Small-scale artificial reef description and settlement measurements

A small-scale two-layer artificial reef structure (with the inner core made of FG-based blend and the outer layer made of limestone) was built and placed at a depth of approximately 1 m during low tides in the bay in Grand Isle, LA (29°14'20.8"N 90°00'14.3"W) on August 8, 2015 (in the same location and at the same time of submersion of the group 2 cylindrical specimens) to investigate overall reef stability and settlement under field conditions (Fig. 1a). The inner core had a volume of 0.810 m^3 and was made of FG-based blend briquettes of dimensions 3.4 cm x 1.9 cm x 1.1 cm. The briquettes were fabricated by using a Komarek B050A laboratory roller machine with a compression pressure of 48 kN and cured for 28 days in laboratory conditions (i.e., 100% humidity and 21±2 ˚C). The FG-based blend used to fabricate the briquettes had an average unit weight of 1750 kg/m^3 and a standard deviation of 7 kg/m^3. The briquettes' average bulk weight was measured following ASTM C29 (2016b) as 963 kg/m^3, with a standard deviation of 41 kg/m^3. The briquettes were placed in geogrid mesh bags (each containing about 20 kg of briquettes) (Fig. 1b). The outer layer was made of gravel-size (5-10 cm) crushed limestone with an average thickness of 0.1 m, volume of 0.613 m^3, and an average unit weight of 2400 kg/m^3. This limestone outer layer was placed to protect the core from wave attack by absorbing the wave energy. The structure had the shape of a pyramidal frustum with a length, width, and height of 2.8 m, 2.3 m, and 0.4 m, respectively. Figs. 1c and 1d show a 3-dimensional view and a sectional view, respectively, of the artificial reef.

The elevation changes at 12 points on and around the reef (shown in Fig. 1c) were measured with respect to the elevations obtained on the day the structures was placed in the field. These elevation changes were recorded every three months for nine months using a standard surveying procedure (Nathanson et al. 2006). The measurements were taken in nine locations corresponding to the corners and midpoints at the base of the structure and in the middle point at the top of the artificial reef (locations #1 through #9 in Fig. 1c). Surface sediment measurements were also taken at three points (locations #10 through #12 in Fig. 1c) located at approximatively 1 m of distance from the reef structure to determine if sediment deposition or scour was taking place around the reef. The elevation changes were measured with respect to a reference point located on a concrete column on land, as shown in Fig. 1a.

Experimental Results and Discussion

Statistical characterizations of compressive strength and relative volumetric expansion after 28-day curing

Sample means (μ), standard deviations (σ), and coefficients of variation (CoV) were calculated for both compressive strength and relative volumetric expansion of the material after the 28-day curing process (Table 2). The compressive strength (μ_{f_c} = 8.9 MPa, σ_{f_c} = 1.4 MPa, and CoV = 15.7%) is significantly lower than the typical strength of ordinary concrete (i.e., 20-35 MPa), but it is more than double the strength needed (i.e., about 4.0 MPa) for breakwater construction (Bigdeli et al. 2018b). The CoV was greater than typically measured from specimens obtained from a single batch of concrete, but it is lower than the concrete variability typically assumed in design applications (Mirza et al. 1979). The relative volumetric expansion (μ_{η} = 6.2%, σ_{η} = 0.9%, CoV = 14.5%) is slightly higher than the value of 6% suggested in Bigdeli et al. (2018b) to avoid potential cracking of the material. However, the difference between this sample average (6.2%) and the threshold for potential cracking (6%) is statistically non-significant (i.e., p-value = 0.130 for the null hypothesis that the sample average is higher than the potential cracking threshold).

Three different probability distributions (i.e., normal, lognormal, and Weibull distributions) were fitted to the experimental data (Figs. 2 and 3) for the compressive strength and the relative volumetric expansion. The chi-square (χ^2) and the modified Kolmogorov-Smirnov (mK-S) goodness-of-fit tests were used to identify the distribution providing the best fit (Box et al. 1978). Because higher p-values generally indicate better fitting between the empirical distribution function of the sample and the cumulative distribution function of the reference distribution, both goodness-of-fit tests suggest that the lognormal and normal distributions provide the best fit to the measured compressive strength and relative volumetric expansion data, respectively (Table 2).

Effects of curing time on FG-based blend strength and relative volumetric expansion

The effect of curing time on compressive strength and relative volumetric expansion is crucial to determine optimal curing times of FG-based blends for different types of applications. The FG-based blend continued to gain strength up to 121 days, after which no significant gain was observed (Table 3). As expected, the strength gain was faster at the beginning of hydration and slowed down with time, most likely due to the rapid formation of ettringite in early ages followed by slower formation of calcium silicate hydrate at later times (Yan and Yang 2000), in a similar fashion to the strength development that is typical of concrete (Metha 1973). At 28 days, the FG-based blend reached an average strength of 7.6 MPa, or 50% of its full strength (≥ 121 days). In contrast, ordinary concrete with Portland cement only as binder reaches 85% to 90% of its final strength after 28-day curing (Metha 1973). After 121 days of curing, the average compressive strength showed only minimal gains, indicating that the remaining hydration rate of the FG-based blend after 121 days was close to zero. It is noteworthy that the average compressive strengths for the FG-based blend after 133, 208, 298, and 393 days (identified in Table 3 with italic characters) were not statistically different with respect to the average compressive strength achieved at 121 days, which supports the hypothesis that the hydration rate of the FG-based blend becomes minimal after 121 days of wet curing under laboratory conditions.

The relative volumetric expansion of the FG-based blend approximately doubled from day 7 ($\mu_\eta = 3.5\%$) to day 28 ($\mu_\eta = 6.2\%$), with no statistically significant change thereafter. This result indicates that the FG-based blend becomes volumetrically stable while still gaining compressive strength, which is consistent with the hypothesis that different chemical reactions produce the strength increase observed at different curing times for the FG-based blend. The long-term volumetric stability of the FG-based blend when subjected to wet curing under laboratory conditions is a desirable property, because it is a necessary prerequisite for long-term stability of the material under field conditions. The volumetric expansion of FG-based blends is mainly due to the formation of ettringite and that volumetric expansions greater than 6.3% generally correspond to the formation of visible cracks in the specimens and a reduction in the compressive strength of this material (Bigdeli et al. 2018b), which were not observed in the specimens prepared for this study.

Effects of prolonged submersion on the compressive strength of FG-based blends

Fig. 4 illustrates the mean compressive strengths and 95% confidence intervals as a function of the curing (laboratory conditions) and submersion time (field conditions). The mean compressive strength increased from 7.6 MPa before submersion (i.e., after 28 days of wet curing in laboratory) to 11.5 MPa after 105 days of submersion (i.e., by approximatively 51%) and then remained practically constant (i.e., no statistically significant change). This result suggests that the hydration process continued in the material even after submersion in brackish water. The prolonged submersion in brackish water under field conditions resulted in a mean compressive strength reduction of 3 to 4 MPa for the FG-based blend when compared to the samples that were cured for the same period of time under laboratory conditions without submersion in brackish water. Based on visual inspections of the retrieved samples, it was hypothesized that this phenomenon could be due to the leaching of the FG-based blend into the water and the resulting increased porosity of the material over time, as noted in Lofton (2017) through scanning electron microscope-energy dispersive X-ray spectroscopy analysis. The compressive strength standard deviations are significantly higher for the specimens in field conditions than for those cured in laboratory conditions. This result is due to the additional uncontrolled variability introduced by the field conditions (e.g., temperature, salinity, currents, interaction with aquatic organisms), which can all affect the compressive strength of the submerged specimens. It is noted here that lower average compressive strength and higher compressive strength standard deviation are generally considered negative effects on the performance of a concrete-like material. However, in this specific case, the strength requirements are satisfied by such a large margin that the observed degradation of the material's compressive strength has a negligible effect on its performance for aquatic applications such as artificial reef construction.

Visual examination of the submerged specimens showed the presence of oysters, crabs, and barnacles covering the surfaces suggesting that the FG-based blend is an attractive material for aquatic organisms (Fig. 5). Fig. 6 shows the cylindrical specimens retrieved at different periods of submersion and after the removal of surface organisms and light cleaning of the surface. The recovered specimens maintained their shape but showed a change of the surface texture, which could indicate an increasing surface porosity for increasing submersion time. This result could also be explained based on the hypothesis of leaching of the material, in combination with the observed holes bored by some of the organisms (e.g., see Fig. 5b and Lofton 2017). It is noteworthy that the FG material does not present hazardous characteristics to human health and the environment and, thus, is not regulated by United States Environmental Protection Agency (USEPA 1990). In addition, leaching studies performed by the authors indicate that the leaching of no constituents of potential concern is above the regulatory limits as measured by a toxicity characteristic leaching procedure (Lofton 2017; Lofton et al. 2018). Thus, it is concluded that the limited leaching of FG-based blend observed in this study does not represent an issue in terms of environmental impacts (Lofton 2017).

Field investigation of artificial reef stability and settlement

The field investigation presented in this study focused on the durability and stability of non-load-bearing artificial reefs (e.g., oyster reefs) built using loose materials on soft sediments that are typical in the US Gulf Coast region. For this type of structures, compressive strength is not a concern and long-term durability is limited to a period ranging between one and a few years. The two major practical issues that control the performance of these structures are (M. Schexnayder, Louisiana Department of Wildlife and Fisheries, Personal Communication 2014): (1) the sinking rate in the soft sediment, which needs to be minimized and reduces with decreasing bulk weight of the material used; and (2) the stability to displacement of the loose material due to currents and waves, which generally increases for increasing bulk weight and grain size of the construction materials. These two issues impose competing constraints on the unit weight and grain size of the construction material, so that optimal combinations of these two properties need to be sought for each specific location.

Table 4 reports the elevation changes at different times of submersion for all measurement points shown in Fig. 1c. Positive values correspond to heave due to soil deformation, structure deformation, and/or sediment deposition; whereas negative values correspond to settlement. At three and six months, it is observed that the elevation changes at the base of the reef were generally small and often positive, most likely due to a combination of soil and structure deformation and very small settlement. The elevation change measurements after nine months show that the top of the artificial reef (measurement point #9) settled by 4.27 cm. This total settlement was a combination of the actual settlement of the structure into the soft soil bed and the changes in the configuration of the structure over time due to environmental actions on the structure, including wave loads, hydrostatic pressure, and structure's self-weight. These results indicate that the sinking rate of the structure with a core layer made of FG-based blend was significantly lower than that for a similar structure made of recycled concrete or limestone, which could have reached between 1/3 and 2/3 of the height of the structure (i.e., 13-26 cm) within the same settlement time (M. Schexnayder, Louisiana Department of Wildlife and Fisheries, Personal Communication 2014). At the same time, the small configuration changes in the artificial reef indicate that the structure is not prone to displacement induced by currents, wave loads, and hydrostatic pressures.

Simplified cost analysis of FG-based blends for artificial reef construction

A simplified cost analysis was performed to compare the cost per unit weight and per unit volume of the proposed FG-based blend with other materials commonly used for artificial reef construction (Table 5). The price ranges of the components used to produce the FG-based blend material were determined as \$3-10/ton for the FG (G. Mitchell, Personal communication, Brown Industries 2016), \$102/ton for PC (USGS 2017), and \$50/ton for class C FA (Rupnow 2012). The price range for crushed limestone and recycled concrete were estimated as \$26-39/ton and \$14-21/ton, respectively, by contacting seven local suppliers for limestone (of which four provided the requested cost information) and ten local suppliers for recycled concrete (of which five provided the requested cost information). The transportation cost was estimated by considering the distance between the sources of material located in Southern Louisiana (one for FG-based blend, seven for limestone, and 10 for recycled concrete) and the site at Grand Isle, LA, and the current range of trucking cost in the State of Louisiana, which was identified as \$0.12-0.18/ton/km (Torrey and Murray 2016). The bulk unit weights of FG-based blend briquettes, crushed limestone, and crushed recycled concrete were taken as 920-1000 kg/m^3, 1265-1380 kg/m^3 (Hansen 2004), and 1200-1450 kg/m^3 (Hansen 2004). The total material cost was estimated as \$40-55/ton (\$42-58/m^3) for the FG-based blend, \$38-69/ton (\$53-104/m^3) for the limestone, and \$27-52/ton (\$36-83/m^3) for the recycled concrete (see Table 5). The proposed FG-based blend has a cost per unit weight similar to that of limestone (with a smaller range of variability) but slightly higher than that of recycled concrete. However, when comparing costs per unit volume, the cost of the proposed FG-based blend is lower than that of limestone and on the lower end of the cost of recycled concrete.

For the specific application of artificial oyster reefs, the most significant comparison is the cost per unit surface of reef. This comparison was made here by assuming a minimum thickness above the seabed of 40 cm (Stokes et al. 2012) after settlement of the reef and calculating the reef thickness at time of construction that would be needed to achieve the minimum thickness after settlement. The average settlements were assumed equal to 3-6 cm for reefs made of FG-based blend (based on the experimental results reported in Table 4) and 13-26 cm for reefs made of limestone or recycled concrete (M. Schexnayder, Louisiana Department of Wildlife and Fisheries, Personal Communication 2014). The costs per unit surface of reef are reported in Table 5. It is observed that the range of cost per unit reef surface for the proposed FG-based blend material is lower than the range of cost for limestone and is close to the lower boundary of the cost range for recycled concrete. Thus, it is concluded that the proposed material could produce significant savings in construction projects of artificial oyster reefs.

Conclusions

In the present paper, the statistical characterization and the time-dependence of compressive strength and relative volumetric expansion for a concrete-like blend based on fluorogypsum (FG) were studied in laboratory and field conditions. Experimentally obtained results show that the compressive strength and relative volumetric expansion after 28 days of curing of an FG-based blend made of 62% pH-adjusted FG, 35% class C fly ash (FA), and 3% Portland type II cement (PC) can be described by the lognormal and normal distributions, respectively. The FG-based blend reached an average 28-day compressive strength of 8.7 MPa. This strength continued to develop until 121 days of curing up to a value of 14.4 MPa, reaching a final value of 15.4 MPa after 393 days of curing in laboratory conditions. The compressive strength of the FG-based blend was also investigated under field conditions. It was found that the material continued developing its compressive strength also after prolonged immersion in brackish water (with an average salinity of 19.82±0.04 ppt), achieving a strength of 11.2 MPa after one year of immersion in field conditions. This compressive strength was in average 4.3 MPa lower than the corresponding compressive strength for the specimens cured in laboratory conditions. The visual examination of the FG-based blend samples recovered after brackish water immersion showed that numerous aquatic organisms were attached to the surface of the samples, which suggests that the proposed FG-based blend is an attractive material for aquatic organisms. Additionally, monitoring a small-scale artificial reef structure placed in the field for nine months showed that the structure settlement rate was significantly lower than that for similar structures made of recycled concrete or limestone. A preliminary cost evaluation of the FG-based blend indicates that this material has a cost per unit weight similar to that of limestone but higher than that of recycled concrete. However, when considering the cost per unit reef surface, which for artificial oyster reef construction represents the most significant parameter, the proposed FG-based blend appears to be economically advantageous when compared to both limestone and recycled concrete. It is also noted here that the FG-based blend used for this study was not optimized for cost and that no allowance was considered for stockpiling cost reduction of by-product material or for other environmental advantages related to the use of this material, e.g., reduction of greenhouse gas emission. Additional studies are needed to optimize the cost of the FG-based blend for the specific aquatic application considered in this work, as well as to quantify the other benefits associated with the usage of the proposed FG-based blend.

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Data availability statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request. The available data consist of the experimental results relative to the individual specimens used to develop Tables 2 and 3 of the paper.

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Tables

Table 1. X-ray diffraction analysis results for FG, FA, and PC (% by dry weight) (Data from Bigdeli et al. 2018b)

Components	FG	FA	PC
Akermanite: $Ca_2Mg(Si_2O_7)$	-	32.6	-
Alite: $3CaO{\cdot}SiO_2$	-	-	70.4
Anhydrite: $CaSO_4$	5.7	6.8	-
Brownmillerite: $Ca2(Al,Fe)_2O_5$	-	29.4	23.3
Fluorite: CaF_2	0.8	-	-
Gypsum: $CaSO_4{\cdot}2H_2O$	93.4	-	1.4
Periclase: MgO	-	5.9	-
Perovskite: $CaTiO_3$	-	3.9	-
Quartz: SiO_2	0.1	20.3	-
Calcite: $CaCO_3$	-	-	4.9

Table 2. Sample mean and standard deviation of the experimental data (n = 20) for the FG-based blend after 28-day curing and corresponding p-values according to two goodness-of-fit tests for three fitted distributions.

	μ	σ	CoV (%)	Distribution	χ^2 (p-value)	mK-S (p-value)
f_c (MPa)	8.9	1.4	15.7	Normal	0.095	0.366
				Lognormal	0.276	0.745
				Weibull	0.027	0.001
η (%)	6.2	0.9	14.5	Normal	0.120	0.057
				Lognormal	0.061	0.016
				Weibull	0.046	0.001

Table 3. Experimental results for compressive strength, f_c, and relative volumetric expansion, η, of FG-based blend in both laboratory and field conditions

Wet curing in laboratory conditions						Immersion under field conditions			
# of specimens	Time (day)	μ_{f_c} (MPa)	σ_{f_c} (MPa)	μ_{η} (%)	σ_{η} (%)	# of specimens	Time (day)	μ_{f_c} (MPa)	σ_{f_c} (MPa)
5	7	5.0	0.3	3.5	0.9	-	-	-	-
5	14	6.3	0.6	5.1	0.8	-	-	-	-
20	28	7.6	0.6	6.2	0.9	-	0	-	-
5	56	10.6	1.2	*6.2*	0.9	-	28	-	-
5	121	14.4	0.6	*6.2*	0.9	-	93	-	-
5	133	*14.5*	1.9	*6.2*	0.9	5	105	11.5	1.6
5	208	*14.6*	1.1	*6.2*	0.9	5	180	*9.1*	1.8
5	298	*14.7*	1.6	*6.2*	0.9	5	270	*11.7*	3.2
5	393	*15.4*	1.0	*6.2*	0.9	5	365	*11.2*	2.5

Note: Italics characters identify average values for which changes are not statistically significant

Table 4. Recorded elevation changes at the artificial reef's location (negative values: settlement, positive values: heave).

Measurement points (Fig. 1c)	3 months (cm)	6 months (cm)	9 months (cm)
1	1.22	-0.30	-1.22
2	-1.22	-5.18	N/A
3	0.61	-1.83	-1.52
4	N/A	N/A	-2.74
5	2.74	0.91	-0.91
6	1.83	1.52	-1.52
7	0.03	1.52	-4.27
8	-1.22	-0.08	-1.22
9	N/A	-0.61	-4.27
10	-6.40	0.61	-13.41
11	-7.01	-8.84	-9.14
12	13.41	8.84	8.53

N/A: Not available

Table 5. Cost estimation of FG-based blend, limestone, and recycled concrete.

Cost components	Cost per unit weight ($/ton*)	Cost per unit volume ($/m^3)	Cost per unit reef surface ($/m^2)
FG-based blend:	**40-55**	**40-61**	**17-28**
Base material	22-27		
Production	2-5		
Transportation	16-23		
Limestone:	**38-69**	**53-104**	**28-69**
Base material	26-39		
Transportation	12-30		
Recycled concrete:	**27-52**	**36-83**	**19-55**
Base material	14-21		
Transportation	13-31		

* ton = 907 kg

Figure captions list

Fig. 1. Artificial reef used for field investigation: (a) location (map data © Google Maps), (b) geogrid mesh bags filled with briquettes of FG-based blend, (c) 3-dimensional view of the reef, and (d) cross sectional view along the long direction of the reef.

Fig. 2. Compressive strength variability of FG-based blend after 28-day curing: comparison between empirical and analytical cumulative distribution functions for three different fitted distributions.

Fig. 3. Relative volumetric expansion variability of FG-based blend after 28-day curing: comparison between empirical and analytical cumulative distribution functions for three different fitted distributions.

Fig. 4. Compressive strength of the FG-based blend as a function of curing time under laboratory conditions and immersion time in field conditions.

Fig. 5. Attachment of diverse sea organisms to the FG-based blend specimens after immersion in brackish water at Grand Isle, LA: (a) attachment of barnacles and presence of crabs, and (b) attachment of oysters and other molluscs.

Fig. 6. Conditions of FG-based blend specimens for field investigation after different immersion time: (a) 0 days (i.e., before immersion), (b) 105 days, (c) 180 days, (d) 270 days, and (e) 365 days.

Figure 1

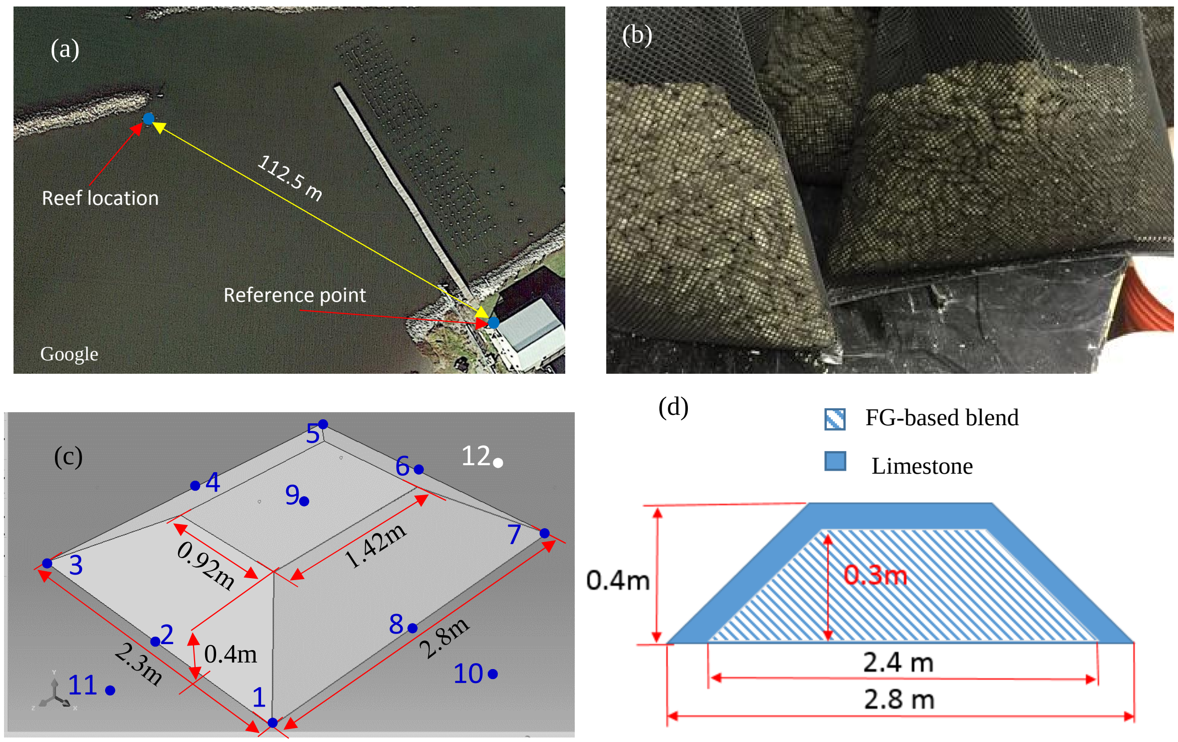
(a)
Reef location
112.5 m
Reference point
Google
(b)
(c)
5
4
6
12
9
7
3
0.92m
1.42m
2
0.4m
8
2.8m
2.3m
11
1
10
(d)
FG-based blend
Limestone
0.4m
0.3m
2.4 m
2.8 m

Figure 2

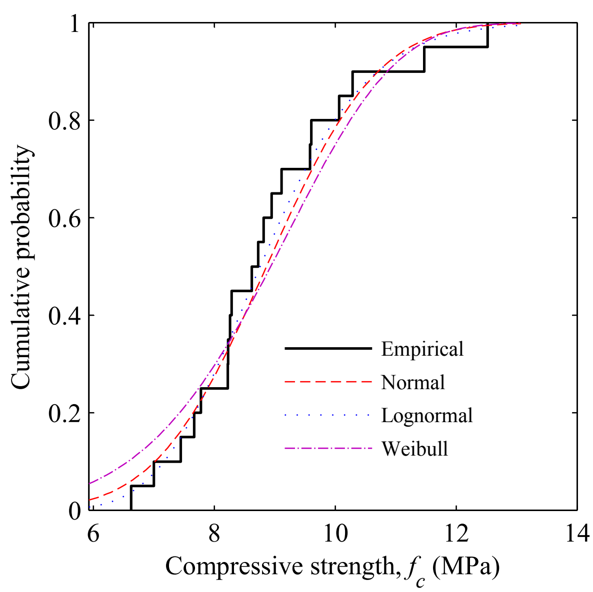
Cumulative probability
Compressive strength, f_c (MPa)
Empirical
Normal
Lognormal
Weibull
0
0.2
0.4
0.6
0.8
1
6
8
10
12
14

Figure 3

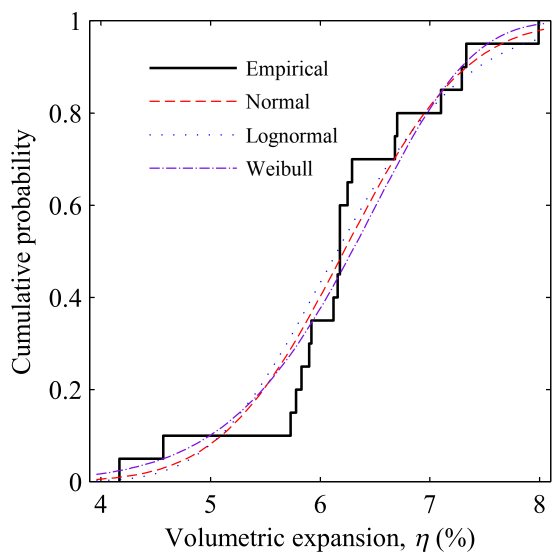
Empirical
Normal
Lognormal
Weibull
Cumulative probability
Volumetric expansion, η (%)
0
0.2
0.4
0.6
0.8
1
4
5
6
7
8

Figure 4

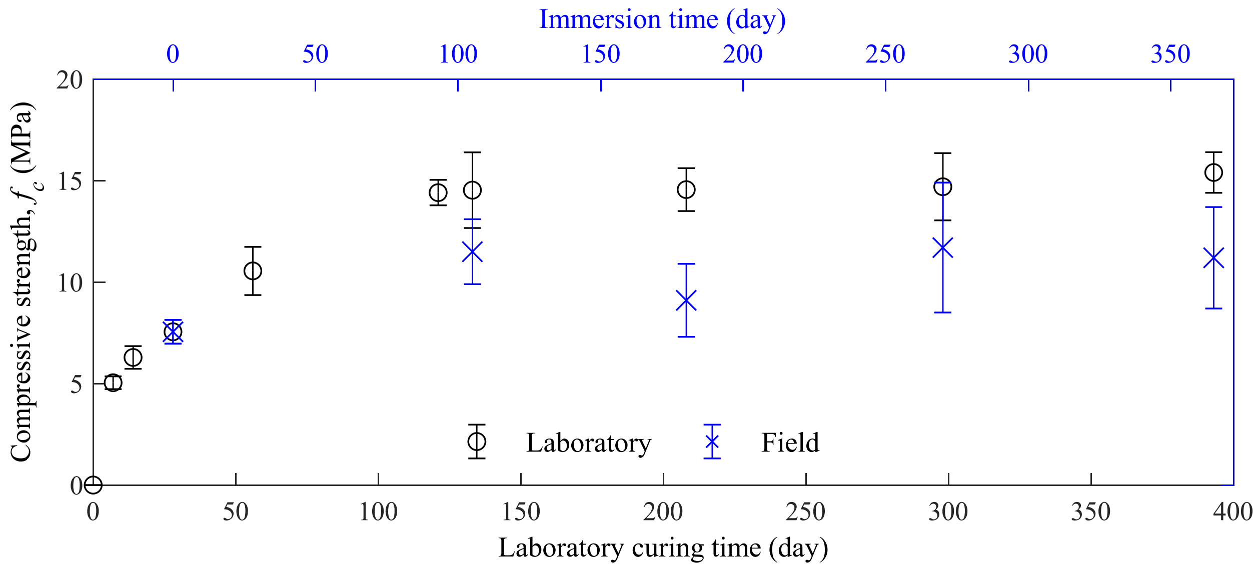
Immersion time (day)
0
50
100
150
200
250
300
350
20
15
10
5
0
Compressive strength, f_c (MPa)
Laboratory
Field
0
50
100
150
200
250
300
350
400
Laboratory curing time (day)

Figure 5

Figure 6